RADIO BY MAIL
National Radio Institute
STUDENTS ALL OVER THE WORLD

NATIONAL RADIO INSTITUTE

Certified Radio-Trician's Course
(REG. U. S. PAT. OFF.)

MUTUAL INDUCTION AND RESONANCE

No. 9FR

Originators of Home Study Radio Courses
ESTABLISHED 1914
Washington, D. C.

FOREWORD

Very many people have the peculiar habit of leafing through a new book and glancing at the illustrations before they start reading it. Ordinarily a procedure of this sort doesn't do any harm, but sometimes we see pictures that look complicated and the result is we tackle the book with the idea that the subject covered is going to be most difficult.

If you have by any chance looked at the illustrations in this lesson you will have noticed that some of them are peculiar looking things—but don't let them give you the impression that it is going to be impossible to understand them.

As far as I know, this is the first time that it has even been attempted to explain impedance and resonance in this scientific manner in a home-study course. And yet there is no reason why it shouldn't be done as it has been proven time and time again that home-study students are as eager to learn as any students, that they are conscientious, and that they are willing to think.

This lesson will require thought, and its value to you will be proportionate to the amount of time and thought you give it. It isn't "baby-food" by any means—it is a scientific treatment of principles of Radio that are vital. Master them—if not the first time you go over the lesson, then the second or third time you go over it.

J. E. SMITH.

Copyright 1931
by
NATIONAL RADIO INSTITUTE
Washington, D. C.

BF2M32031

Printed in U.S.A.

MUTUAL INDUCTION BETWEEN COILS

When we studied inductance we learned considerable about the effects of mutual induction between turns of wire—we saw how a voltage could be induced in a second independent wire by the action of the magnetic field about another wire which carried current.

You will remember that when a voltage is induced in a second circuit, a magnetic field is built up about the conductors of the second circuit which in turn induces a back e.m.f. in the conductors of the first circuit. You will remember, too, that inductance in a coil is the result of self-induction in the individual turns and mutual induction between adjacent turns of wire; and that the effect of inductance is only apparent when the current flowing through the conductors is changing in value.

Now we are going to study the effects of mutual induction between coils, a phenomenon that is put to many practical uses in Radio. The best way to go about studying these effects is by performing some very simple experiments using coils.

Let us take about 100 feet of No. 20 insulated copper wire and wind it on a cardboard tube about 3 inches in diameter. There will be about 127 turns. When the coil is completed we have what is called a helix (from the Greek word meaning "spiral"), or a solenoid, also from the Greek meaning "like a hollow tube." The two words are often used interchangeably although a distinction should be made—the word solenoid referring either to a single or multi-layer air core coil while helix should be used only for single layer air core self-supported coils.

If we attached two leads from a dry cell to the two ends of the coil winding and allowed the current to flow through the turns, a magnetic field would be built up through and around the coil. With a small compass we can determine in which direction the magnetic lines of force flow around the coil. (See Fig. 1.) Suppose we reversed the battery connections to the coil—the compass will show that now the lines of force are moving in the opposite direction.

Now to continue our experiments we shall have to wind another coil. Let us make this one smaller than the first one—let us say we use a coil form 2 inches in diameter instead of 3. Having built up our second coil we connect the battery to this coil and instead of a battery we connect a sensitive voltmeter to the ends of the winding of the first coil as in Fig. 2 and then we're ready to start noticing things.

First we place the smaller coil inside the larger coil and then draw it out rapidly. If we keep our eye on the voltmeter we will notice that the needle deflects as we separate the coils. This deflection might be just a small kick but even the slightest deflection will tell us what we want to know—that a voltage has been induced in the second coil. But when the small coil was at rest inside the larger coil, there was no voltmeter deflection.

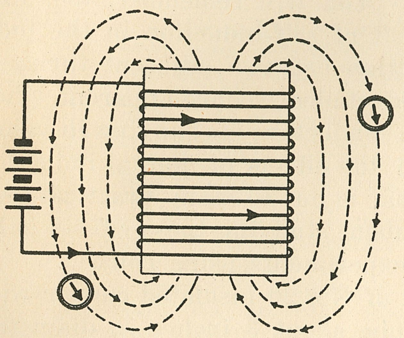


Fig. 1

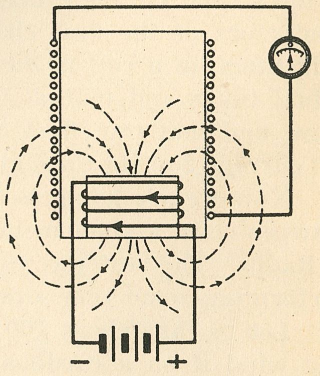


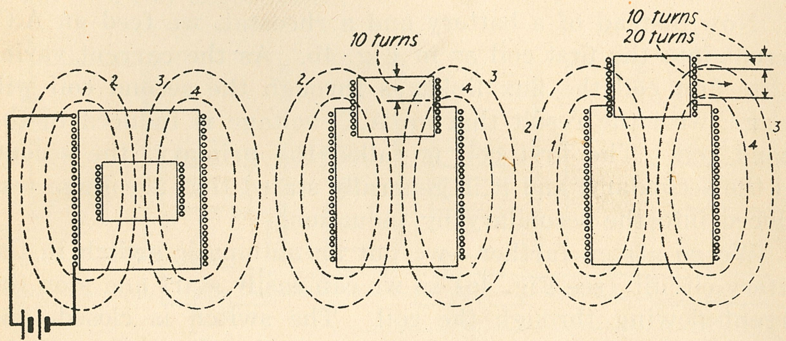
Fig. 2

Now what conclusions can we draw from this little experiment?

We know that there is a magnetic field about the coil which is connected to the battery—the result of the current flowing through the coil windings. When this coil is stationary inside the larger coil, no voltage will be induced in the latter because the magnetic field is stationary and you learned in the lesson on inductance that it takes a moving magnetic field to induce a voltage. When we drew the coil out we obtained this moving magnetic field. The lines of force about the smaller coil cut the turns of wire on the larger coil and a voltage was induced in the turns of the latter.

There is a very important principle that you should master at the present time. Study carefully Fig. 3a. The smaller coil is inside of the larger diameter coil. Let us say that the smaller coil has 50 turns. The large coil produces 4 magnetic lines due to the current flowing through it (of course, many more are produced but 4 is chosen because it is simple to show). Four of these lines circle through the large and the small coil. We say that they link with the large and small coil. In the case of the small coil there are 50 turns, so for each turn four lines link with it, or 50 × 4 for the entire small coil. This is usually spoken of as 200 flux-turn linkages.

In Fig. 3b, the small coil is pulled up. The number of lines does not change, but perhaps 10 of its turns on the smaller coil no longer have flux threading through them by the lines 1 and 4 and we lose 10 × 2 or 20 linkages in this position. In 3c the coil is pulled farther out so that 10 turns of the coil no longer have flux at all through them and 20 turns are not linked with lines 1 and 4; that is, we have lost $10 \times 4 = 40$ and $20 \times 2 = 40$, a total loss of 80 linkages. We might say that in Fig. 3a, there were 200 linkages, in 3b, 180 linkages, and in 3c there were 120 linkages.



(a) (b) (c)

Fig. 3

Here's the important fact. *If through any coil the flux linkages change, an e.m.f. will be induced in that coil.* From this explanation it is easy to see that it makes no difference whether we move the large or the small coil, if the linkages through the small coil are changed an e.m.f. will be induced. Of course if you pull the small coil through the top the induced e.m.f. will be in one direction and if it is pulled through the lower end, in the other direction.

From this we can assume that by moving the coil in and out of the larger coil, an A.C. voltage will be induced into the smaller coil.

Now suppose we fix one coil inside the other, the small coil inside the large one. To one we connect a source of e.m.f. (a battery) in series with a variable resistance as in Fig. 4a. To the other coil we connect a sensitive milliammeter. The rheostat allows us to vary the current in this coil from zero to maximum, let us say from 0 to 1 ampere. This, in turn, causes from 0 to 100 magnetic lines to thread through it. The second coil ~~also~~ has ~~0 to~~ 100 magnetic lines of force threading through it, when maximum current flows in the first coil. As we increase the lines from zero to 100 the flux linkages in the second coil increase and of course an e.m.f. is induced. As the current in the first coil is reduced the flux linkages are reduced and an induced voltage results. It makes no difference whether the linkages increase or decrease, a voltage will be induced. But the faster you change the flux linkages the greater will be the induced e.m.f.

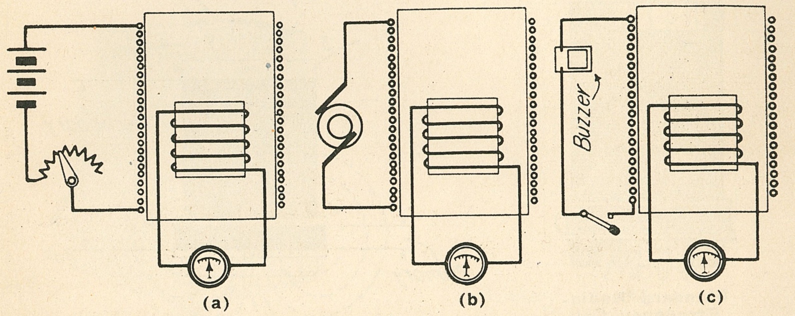
Now instead of a battery and a rheostat, we feed an A.C. current into the first coil as in Fig. 4b. As the current varies in the first coil the flux linkages through the second coil will change, with the result that an A.C. voltage is induced in the second coil. The first coil is called the primary, the second coil the secondary, and it is generally stated that a voltage was induced into the secondary by induction.

We go a step farther—we put an automatic switch in the battery circuit (see Fig. 4c) so we can easily start and stop the current flowing through the coil. The switch is closed—the meter needle connected to the larger coil will show a slight deflection but after a momentary kick it will return to zero position. The switch is opened—the meter needle shows another kick.

From what we know of induced voltages we can explain this very easily. At the instant we close the switch, current begins flowing through the turns of the coil and a magnetic field builds up. As it builds up the varying flux linkages through the larger coil induce a voltage into it. When the inductance of the small coil no longer affects the value of the current flow the field has reached maximum and remains stationary and a stationary field will induce no voltage, therefore the meter needle returns to zero. But when we open the battery circuit, the magnetic field about the small coil begins to collapse and as it collapses it induces a voltage into the turns of the inner coil in the opposite direction as will be shown by the direction in which the meter kicks.

If we were to open and close the switch rapidly, an A.C. voltage would be induced in the larger coil. This is interesting, for we are feeding into one coil an interrupted direct current and getting out of the other coil an A.C. voltage. Direct current flows through one coil in pulses and so it might be considered as pulsating D.C., or a direct current plus an A.C. current—in the second coil the current flows in positive and negative alternations. By means of an arrangement like this energy is transferred from one circuit to another and in the process of transfer, it is transformed from pulsating D.C. to A.C. Such a device is used extensively in commercial fields and is called an induction coil, which is really a special kind of "transformer."

We are going to learn more about transformers in the next chapter. But before we go on we must consider various aspects of our two coil experiment.



(a) (b) (c)

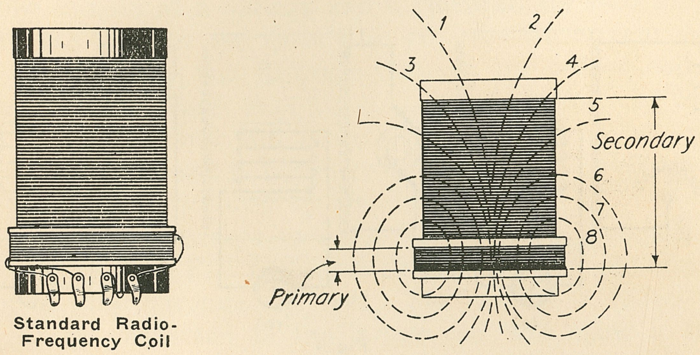
Fig. 4

You know that when a voltage is induced into the secondary by the action of the changing flux linkages about the primary, a current will flow in the secondary circuit (the circuit including the smaller coil and the meter). If it weren't for this small flow of current the meter needle would not kick as it does. But as the current flows through the windings of the secondary a field is built up about it, opposite in direction to the original field about the first coil. This naturally follows from Lenz's law which you learned in the lesson on inductance, to the effect that the field about a conductor in which a current is induced opposes the field which created it. In other words, it reduces the original flux and cuts down the flux linkage. As far as the primary is concerned it opposes the current in it by inducing into it a counter-e.m.f. Or we might say it makes the primary behave as if it had an inductance connected in series with it.

If the primary already has inductance, its apparent inductance is decreased, the decrease due to induction from the secondary to the primary. The reduction inductance due to mutual induction is called mutual inductance.

TRANSFORMERS

Air core transformers used in the R.F. stages of Radio receivers are essentially like the one described although both windings are usually wound on the same form as in Fig. 5a, and there are usually more turns in the secondary winding than in the primary winding. The primary is always connected to the source of electric power, usually the plate of a vacuum tube. Energy is, of course, transferred from the primary to the secondary by mutual induction. In other words, the primary is in the input circuit and the secondary is in the output circuit.



Standard Radio-Frequency Coil
(a)

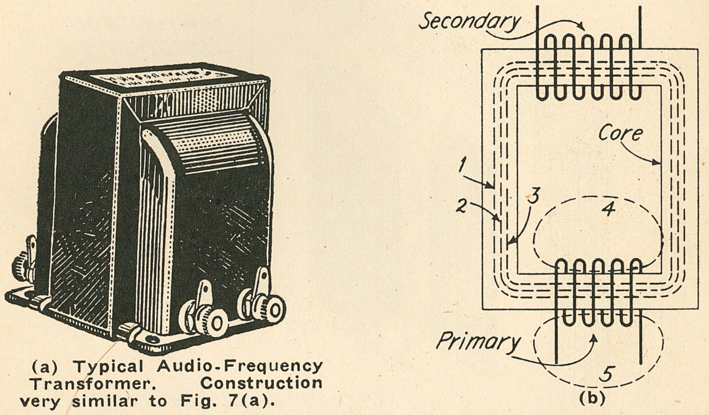
(b)

Fig. 5

When a transformer has more secondary turns than primary turns, it is said to have a step-up ratio. By this we mean that if all the flux about the primary links with the secondary turns the output voltage would be greater than the input voltage, depending upon the ratio of secondary to primary turns. Thus if the primary consisted of 10 turns and the secondary of 100 turns, if the input voltage were 1 volt and if there were no loss of flux linkage, the output voltage of the secondary would be 10 volts. But in an air core transformer there is considerable loss of flux linkage first because air is not a particularly good conductor of magnetic lines and secondly because of the position of the secondary with respect to the primary—both on the same form and separated from each other. Other factors in the coil make-up are more important than the turn ratio, as we shall see when we study more about R.F. systems.

To visualize the reduction in flux linkages in R.F. transformers, study Fig. 5b. This is an exact schematic of a commercial radio frequency coil. The primary produces a flux which threads through the secondary as shown. Notice that only lines *1, 2* ~~and~~ *3* and 4 link with *all* the secondary turns (complete linkage). Again observe that lines ~~*4*~~, *5, 6, 7* and *8,* cut fewer and fewer of the secondary turns, that is, flux-turn linkages are lost. This is referred to as leakage, which is an important problem in any transformer.

The output of the detector tube as you know is direct current which is pulsating at audio frequencies. In the detector tube the audio frequencies are separated from the radio frequencies. From this point on we are interested in developing as much voltage as we can so there will be plenty to operate a loudspeaker. For this reason different types of transformers are used to connect vacuum tube A.F. stages—transformers having iron cores and having the secondary winding wound directly over the primary winding.



(a) Typical Audio-Frequency Transformer. Construction very similar to Fig. 7(a).

(b)

Fig. 6

Soft iron is a much better conductor of magnetic flux than air and audio frequency transformers (see Fig. 6a) are designed so that the magnetic circuit is complete and the flux is confined to this circuit. In transformers of this kind in which "coupling" is said to be high or tight, because practically all the flux of the primary links with the turns of the secondary, the turn ratio of secondary to primary determines the ratio of induced voltage to input voltage. If the transformer has a turn ratio of 3 to 1, that is, the secondary has three times as many windings as the primary, the voltage induced in the secondary will be three times the voltage fed to the primary.

Without question the iron core transformer is one of the most valuable devices in Radio, in fact in all electrical circuits. A schematic is shown in Fig. 6b. When current flows through the primary, flux is created. Due now to the presence of the iron core, the magnetic lines are concentrated through its length as shown by lines *1, 2* and *3*. Perhaps a few magnetic lines (and they are comparatively small) will not flow along the iron path but as shown by lines 4 and 5. Obviously lines *1, 2* and *3* link with the secondary and are responsible for the induced e.m.f. in the secondary. Now when the primary current varies, as for example when it is connected to an A.C. source, the flux linkages with the secondary will vary. Since leakage is reduced to a very small amount, the turn ratio formula will be almost exactly accurate.

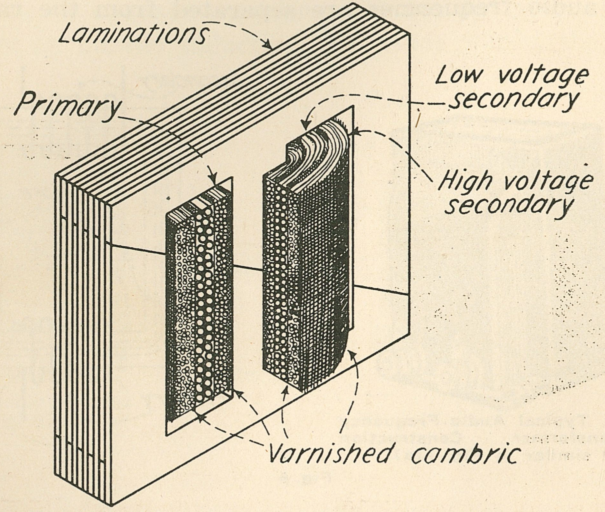


Fig. 7(a)

You will notice that this step-up applies only to voltage. But power is not generated in the transformer so that an increase in voltage must be accompanied by a decrease in current. Suppose we have a large transformer with a step-up ratio of 10 to 1 and we fed into the primary 100 watts of power, 100 watts at 10 volts. This means that in the primary circuit, there are 10 amperes of current and 10 volts pressure ($P = E \times I$). Assuming there are no losses in the transformer the output voltage will be 100—it has been stepped up from 10 to 100. But what about the current—the power must be the same, 100 watts according to the law of conservation of energy? In the secondary circuit the current is only one ampere for $100 \times 1 = 100$ watts.

The cores of modern audio frequency transformers are laminated, that is, they are made up of thin sheets of iron tightly clamped together but insulated from each other usually only by the scale present on sheet iron. The purpose of the lamination is to reduce losses in the form of eddy current losses. The magnetic flux would induce very small currents in a solid iron core, which would result in losses due to the resistance of the iron. However, this matter of eddy current losses and another loss known as hysteresis requires rather lengthy treatment so we can't go into it here—it will be considered in detail when we study magnetic circuits.

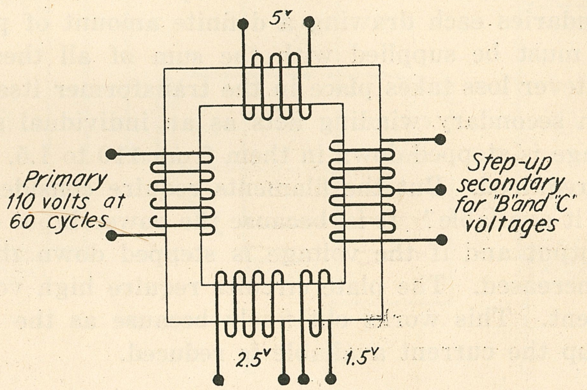

5ᵛ
Primary 110 volts at 60 cycles
Step-up secondary for "B" and "C" voltages
2.5ᵛ
1.5ᵛ

Fig. 7(b)

Now we come to the other type of transformer used in radio receivers—the transformer used in the power pack. See Fig. 7a. This is much larger than the ordinary audio frequency transformer. It is also wound on an iron core but it differs from the types of transformers we have been studying in that it has more than one secondary winding. These secondary windings (shown schematically in Fig. 7b) must supply the various voltages used in the receiver, the A, B and C voltages. As the voltages required to heat the filament are comparatively small, 1.5, 2.5 or 5 volts, there must be a large step-down ratio between the primary and these secondary windings. As these transformers are usually designed to transform 110 volt house lighting current, the step-down ratio for the 1.5 volt winding will have to be ~~100~~ 110 to 1.5, that is, if there are 1000 turns on the primary there will be ~~11.5~~ 13.6 turns on the secondary. The winding which supplies 5 volts will have a step-down ratio of ~~100~~ 110 to 5.

As the B voltages required are considerably higher than 110 volts, a step-up ratio must be employed, that is, the secondary winding supplying the plate circuits will have more turns than the primary.

There is only one secondary B winding because the output of this winding is rectified, and various B voltages are obtained by tapping a resistor across the output of the rectifier tube.

Of course we must remember that we can't get any more power out of the transformer than we put into it. If there are five secondaries each drawing a definite amount of power, the primary must be supplied with the sum of all these powers plus whatever loss takes place in the transformer itself.

Each secondary winding acts as an individual secondary. The voltage is stepped down in them from 110 to 1.5, 2.5, and 5 volts as required. But the filaments require considerable current. Is it available? It is, because the power input equals the power output and if the voltage is stepped down the current will be increased. The plate circuits require high voltage and low current. This works out finely because as the voltage is stepped up the current available is reduced.

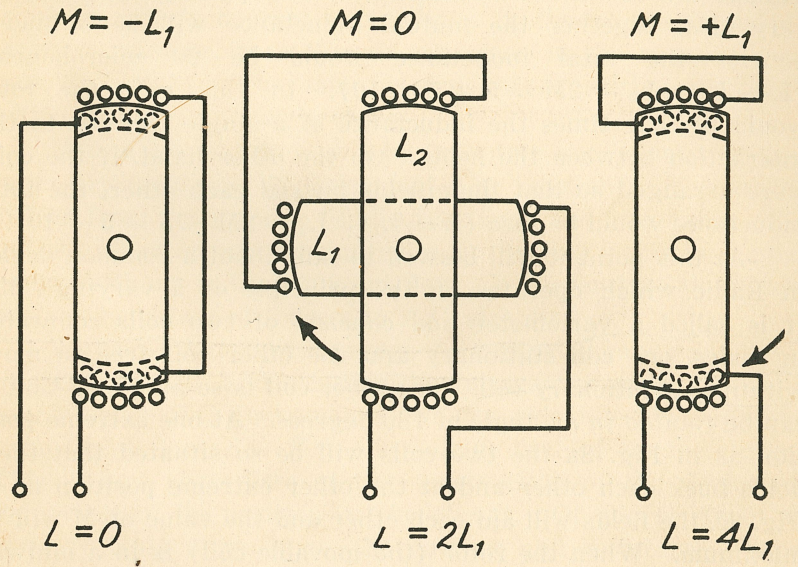
THE EFFECT OF MUTUAL INDUCTION ON INDUCTANCE

It has been thoroughly impressed on your mind that inductance is the result of mutual induction between turns of a coil and self-induction in the individual turns. Bearing this in mind, we are going on now to talk about the effect of mutual induction between coils on the inductance of those coils and from now on whenever we speak of mutual induction we shall mean mutual induction between coils.

It is a simple matter to realize that when a transformer is used as a device to couple circuits the inductance of the windings is placed in the circuit to which the windings are connected. But that isn't all there is to it. The inductance of a coil is dependent on the field about the coil. Therefore if we have two coils with their fields interacting it is reasonable to suppose that the inductance of each coil will be changed because of this interaction.

The effect of mutual induction between coils on the inductance of the coils is called mutual inductance and the symbol is "M." The value of the mutual inductance naturally depends on the extent to which the fields about the two coils link. If the two coils are so far apart that there is practically no flux linkage, then the value of M would be zero.

Now let us imagine the two coils connected together in series. If they are placed so that their magnetic fields link they are said to be in series aiding connection. If they are connected so that their fields "buck" each other, the connection is said to be series opposing.



(a) (b) (c)

Fig. 8

The total inductance of two coils connected in series is equal to the inductance of one plus the inductance of the other plus or minus twice the mutual inductance. In symbol form this is:

$$L = L_1 + L_2 + 2M \text{ (series aiding)}$$
$$L = L_1 + L_2 - 2M \text{ (series opposing)}$$

These formulas are important because mutual inductance is one of those things that you can't measure directly—you have to get at it by round-about methods. Laboratory procedure for calculating the value of M is essentially the same as the proincludes total inductances.

cedure we just went through. The individual inductances of the two coils are measured, then the two coils are connected in series and the inductance of the whole business measured. Then knowing L, L_1 and L_2 it is not a difficult matter to calculate the value of M, taking into consideration the positions of the coils with respect to each other.

Let us say that each has an inductance of 5 microhenries. If these could be so placed that all the flux links—which is impossible in actual practice in the case of air core coils although leakage can be cut down to a minimum by placing the windings very close together the mutual inductance will be 5 microhenries—the total inductance would be 20 microhenries ($L = L_1 + L_2 + 2M = 5 + 5 + 10$). In this case the total would be four times the inductance of a single coil due to the interaction between the fields. On the other hand, if the coils were arranged so that their fields bucked each other, the total inductance would be zero ($L = L_1 + L_2 - 2M = 5 + 5 - 10$).

At this point it will be well to talk about a common device in Radio which operates on the principle of a varying "M." It is called a variometer and consists of two coils connected in series, one coil stationary and the other coil free to move within the stationary coil. The inner coil is so arranged that it can be rotated in an angle of 180 degrees. At one extreme position as in Fig. 8a the two coils will be so situated that their fields buck each other and at the other extreme position as in Fig. 8c, the fields will aid each other and the value of M will be maximum. When the rotor (the movable coil) is in a midway position as in Fig. 8b, the fields do not link and the inductance of the device will be the sum of the inductance of the two coils.

IMPEDANCE IN SERIES CIRCUITS

In previous lessons we learned about the magnitude of voltage and current in circuits containing resistances of different values, both in series and in parallel. We learned some extremely important principles which you must always bear in mind, such as Ohm's law, which states that the current in amperes through any resistance multiplied by the resistance in ohms equals the voltage drop across the resistor in ohms. We learned that this holds true regardless of the position of the resistor in the circuit, no matter how complicated that circuit may be.

You will remember that when resistors are placed in series, the voltage across them is the sum of all the individual voltages across the individual resistors, and that the current through each resistor is the same; that when resistors are placed in parallel, the voltage across each resistor is the same and the current in the main lead connected to the parallel resistors is the sum of all the currents in the individual resistors; that even here Ohm's law holds true for any individual resistor.

In the lessons on inductance and capacity in A.C. circuits, we learned that inductive reactance,* measured and expressed in ohms, affects current and voltage in the circuit in quite a different manner, even though expressed in the same units as pure resistance. The same is true of capacitive reactance* which is also expressed in ohms.

You might rightly ask why inductive and capacitive reactance are measured in ohms just like resistance, if reactance differs from resistance. While reactance and resistance differ in their effect on current and voltage, they have this in common —they both act to limit current flow. It is even true that Ohm's law can be extended for use in A.C. circuits.

We know that if we measure the current through any device in a D.C. circuit, and measure the voltage across the device, of course using D.C. instruments, we can calculate the resistance from Ohm's law, $R = E/I$, the voltage divided by the current. This is true regardless of the construction of the device and regardless of its position in the circuit. Of course, from the same formula if we know the current and resistance we can calculate the voltage drop, or if we know the voltage and the resistance we can calculate the current.

In A.C. circuits we can follow the same procedure. If we use an A.C. voltmeter and an A.C. ammeter and if with these we measure the A.C. voltage and the A.C. current through any device regardless of its position in the circuit (except devices that generate an e.m.f.), by Ohm's law extended for A.C. use, we can calculate the extent to which the device holds back current flow. We divide the volts by the amperes and our answer is in ohms. But because we are dealing with an A.C. circuit, these ohms do not represent resistance but *impedance* (Z).

---

*Inductive reactance is equal to $2\pi fL$ which is 2×3.14 times the frequency in cycles times the inductance in henries. The symbol is X_L. Capacitive reactance (X_C) is equal to $\frac{1}{2\pi fC}$ which is 1 divided by 2×3.14 times the frequency in cycles, times the capacity in farads.

The word impedance is a very useful one as it includes everything that holds back (impedes) the flow of current—that is, it includes both ohmic resistance and reactance, inductive and capacitive. Our combination of resistance and reactance may be a series or a parallel combination, it doesn't make any difference, the voltage divided by the current is the A.C. impedance in ohms.

Still if we are considering the impedance of a single device, as of a condenser, we do not call it impedance but capacitive reactance. In the same way if our device is a coil, we call the ohmic value inductive reactance, never inductive impedance. If the device is a resistor, we call it merely a pure resistance. In this lesson we are going to learn to what extent reactances and resistances in series and in parallel impede the flow of current in A.C. circuits.

But before we go on to talk about impedance in series circuits, we must be sure we understand phase relations in A.C. circuits and what effect on phase a condenser or a coil will have.

You know that an A.C. voltage always starts from zero value and rises to a maximum value in what we call 90 degrees. In another 90 degrees it reduces to zero. In the next 90 degrees the voltage is at maximum again but acting in the opposite direction—you can call it negative voltage if you wish. In the final 90 degrees the voltage returns again to zero. Thus it took 360 degrees for the voltage to complete what we call a complete cycle. As far as the time is concerned, it might have been an hour, a minute, a second, anything. But whatever it is, the time is called the *period*.

An A.C. voltage applied to a device causes the current to flow through it depending on the impedance of the device. If the current is at a maximum when the voltage is maximum, zero when the voltage is zero, negative when the voltage is negative, then we say the current and voltage are in phase. But in many A.C. circuits the voltage and current are not in phase. The voltage may be at a positive maximum when the current is zero, just beginning to flow in a positive direction. Then we say that the voltage *leads* the current by 90 degrees. Or the voltage may be zero, just entering the positive alternation and the current may be at maximum positive. Then we say the voltage *lags behind* the current by 90 degrees. From this we can see that the voltage may lead or lag behind the current. But the angle of difference, called the phase angle, is not often 90 degrees—in fact in a complete circuit the phase angle never is 90 degrees. It is always something between zero and 90 degrees, depending, as we shall see later, on the combination of reactance and resistance in the circuit.

In Radio we like to represent the electrical degrees denoting a phase difference by an actual angle on paper. Look at Fig. 9 carefully. Visualize line I_1 rotating in a counter-clockwise direction, taking positions I_2, I_3, I_4 and I_5. Considering line *OV* as the reference line, I_2 lags behind *OV* by 45 degrees. I_1 lags *OV* by 90 degrees. Now if we consider line *OV* as the voltage line and I_2 as current, then the current will lag the voltage by 45 degrees.

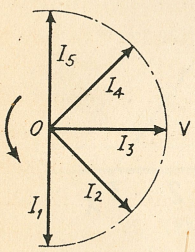
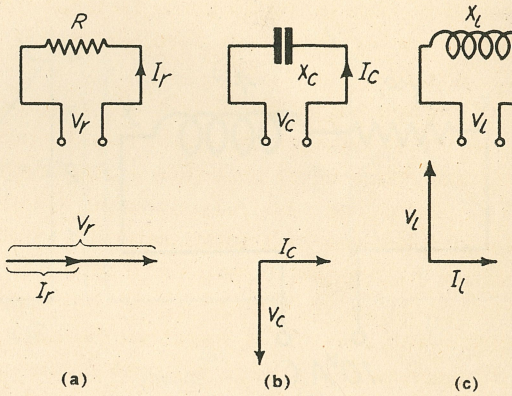


Fig. 9



(a) (b) (c)

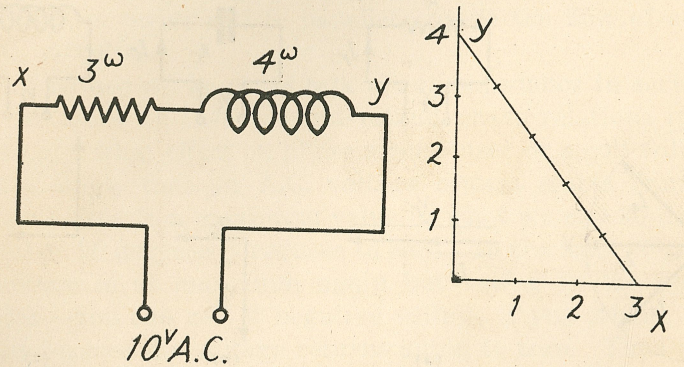
Fig. 10

If we consider I_3 we see that in this case the current and voltage are in phase. Considering line I_4 we see that current is leading voltage by 45 degrees. ~~Likewise line I_5 shows that current is leading voltage by 45 degrees~~. Likewise line I_5 shows that current is leading voltage by 90 degrees.

Every device in an A.C. circuit has a definite impedance, a definite voltage drop across it. There is a definite amount of current flowing through it. And finally there is a definite relationship in phase between the voltage and current. But no matter where a resistance is placed in a circuit and no matter what the phase angle between current and voltage might be in the rest of the circuit, the voltage and current through the resistor are exactly in phase. This is shown schematically in Fig. 10a. Notice that the voltage length is shown on the same line as the current length. By this we represent that they are in phase.

On the other hand, no matter where a capacity is placed in a circuit, complicated or simple, the current always leads the voltage across it by 90 degrees. This is shown in Fig. 10b. Likewise, no matter where an inductance is found in a circuit the current through the inductance is always 90 degrees behind the voltage across it as shown in Fig. 10c.

What we have said about the voltage and current through coils, condensers and resistors, is true whether the supply voltage is 60 cycles or 1500 kilocycles per second, provided the device is a pure capacity, a pure inductance or a pure resistance. And the voltage across the device divided by the current through the device is always the reactance in ohms (in the case of a condenser or a coil), or the resistance in ohms (in the case of a resistor). In other words, Ohm's law is strictly applicable in all its three forms: $I = E/Z$; $E = I \times Z$; $Z = E/I$ — which is strictly Ohm's law even though we use Z as the symbol for impedance instead of R for resistance.



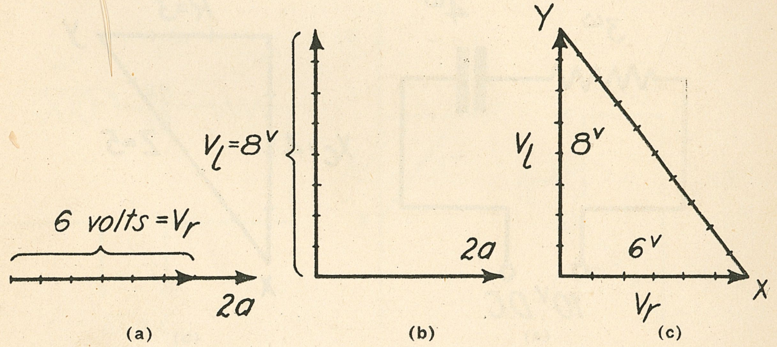
(a) (b)

Fig. 11

Now suppose we have a series circuit containing a three ohm resistor and a coil having an inductive reactance of four ohms as in Fig. 11a. Also connected in the circuit is a ten volt A.C. generator. What we want to know about this circuit is the voltage across the coil and the resistor, and what is the phase relation between voltage and current across the terminals x and y.

Since both devices are in series, it is obvious that the same current will flow through each. What is the value of this current? From the formula just stated we know it will be 10 volts divided by the impedance. But is this impedance 7 ohms $(3 + 4)$? Not at all. If there were two resistors in the circuit we could add their resistances to obtain the total resistance. But when there is a resistance in series with a reactance the total impedance cannot be obtained merely by addition.

A Radio-Trician can work out the total impedance in this way—graphically. Starting out with two straight lines at right angles to each other as in Fig. 11b, the horizontal line representing current and the vertical line representing voltage, or if you prefer, considering the horizontal line as representing resistance and the vertical line representing inductance, we mark off on the resistance line three units, representing three ohms. On the vertical line we mark off four units representing four ohms of inductance reactance. With a ruler draw the line x-y. The length of this line represents the impedance. If you measure it you will find that it is five units long and as we have represented one ohm by one unit, the total impedance in the circuit is five ohms.



(a) (b) (c)

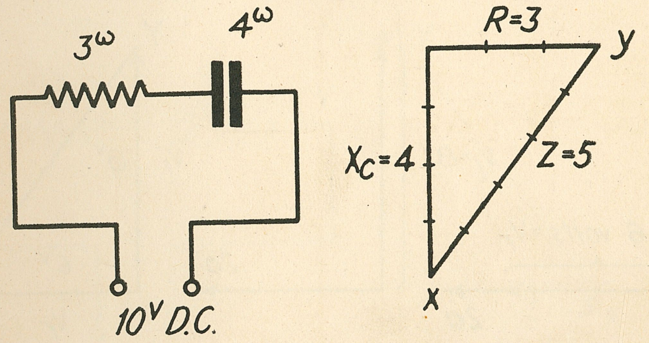
Fig. 12

Knowing the total impedance and the voltage we can calculate the current from Ohm's law for A.C. circuits. It is $10 \div 5$ which is 2 amperes.

Now that we know the voltage, the current and the impedance of the circuit we can make a number of calculations. For example, we can calculate the voltage across the resistor. If the resistance is three ohms and the current through the resistor is two amperes then the voltage across it will be 3×2 or 6 volts. We can calculate the voltage across the inductance in the same way, $4 \times 2 = 8$ volts. But here we get into trouble for

8 + 6 = 14 volts. And the generator voltage is only 10. Where did we make our mistake? We didn't take into consideration any phase shift. Knowing that the voltage can't be higher than 10, we can reason that the phase difference must account for the difference between 14 and 10 volts.

The 6 volts across the 3 ohm resistor are in phase with the 2 amperes of current through the resistor. This is represented in Fig. 12a. The 8 volts across the inductance are always 90 degrees ahead of the current which in this case is 2 amperes. See Fig. 12b. But the current through the coil and the current through the resistor are the same. Therefore we may represent them as in Fig. 12c, both drawn to the same scale. This figure tells us that the voltage across the resistor is 90 degrees ahead of the voltage across the inductance. Now let us add 6 + 8 in this diagram, drawing a vertical line upward from the horizontal line on which we have marked 6 volts (6 units), the vertical line representing 8 volts (8 units). Then if we draw a line connecting X and Y, the line XY will represent the total voltage. In this way we add voltages and at the same time take into consideration the phase differences.



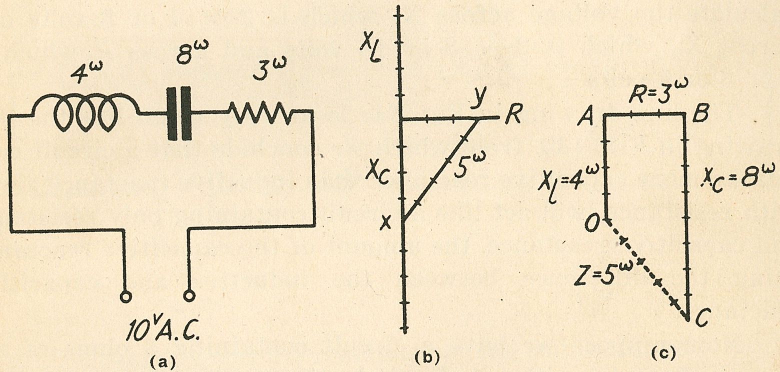
(a) Fig. 13 (b)

From this it can be seen that voltages in A.C. circuits must be added in the same way as reactance and resistance are added.

Now refer to Fig. 13a in which is shown a series circuit containing 3 ohms of resistance and 4 ohms of capacitive reactance. What is the total impedance? Here again we start out with a horizontal line to represent resistance and we draw a vertical line to represent capacitive reactance but in this case the line extends down from the resistance line (Fig. 13b) to show that a capacity causes the voltage to lag behind current. Then we lay off 3 units for the resistance and 4 units for the capacitive reactance and draw the line x-y. Measuring the length of x-y we find that it is again 5 units, or in other words the total impedance in the circuit is 5 ohms. From Ohm's law we can see that the current will be 10 ÷ 5 which is 2 amperes.

We have taken small values of resistance and reactance for convenience. In practice, however, these values may be anything from a fraction of an ohm to thousands of ohms.

In Fig. 14a we have a still more complex circuit—a series circuit containing a coil having 4 ohms of inductive reactance, a resistor having 3 ohms of resistance, and a condenser having 8 ohms of capacitive reactance. How do we go about obtaining the total impedance in a circuit of this sort? What is the current and what is the voltage across each part?



(a) (b) (c)
Fig. 14

The reactances and the resistance must be added in the same manner as before, but in this case we will have a vertical line extending upward and another vertical line extending downward from the reference line (Fig. 14b), because we have both capacitive and inductive reactance in the circuit. We lay off 3 units on our resistance line, 4 units on the X_l line and 8 units on the X_C line. But capacitive reactance shifts phase. Therefore to find the total *reactance* in the circuit we must subtract one from the other—that is, the smaller from the larger. We subtract 4 from 8 which leaves us 4 ohms of *capacitive* reactance. Therefore we count down on the X_C line 4 units and draw a line from x to y. The length of this line represents the total impedance in the circuit (5 ohms).

in a direction opposite to the shift caused by inductive reactance.

We might have done this same thing in a slightly different manner. We might have chosen an arbitrary point as at *O* in Fig. 14c. Starting at *O* we draw a vertical line upward, 4 units long to represent 4 ohms of inductive reactance. Then from point *A* we draw a horizontal line 3 units long to represent 3 ohms of resistance to point *B*. From point *B* we draw a vertical line downward, *8* units long to represent the capacitive reactance. Connect points *O* and *C* and the line *OC* represents the total impedance in the circuit.

Compare this second method with the first method and you will find that it is essentially the same.

Measure line *x-y* in Fig. 14b or line *OC* in Fig. 14c. Each is 5 units long, meaning that the total impedance in the circuit is 5 ohms.

Knowing the impedance we can calculate the current through the circuit. It will be 10 ÷ 5 or 2 amperes. From this we can calculate the voltage across X_l which is 2×4 or 8 volts and across X_C which is 2×8 or 16 volts and across *R* which is 2×3 or 6 volts.

The line drawing in Fig. 14c looks very much like the line drawing in Fig. 13b, from which we conclude that a circuit containing more capacitive reactance than inductive reactance along with resistance, will act like a circuit containing only resistance and capacitive reactance, the amount of the capacitive reactance being the difference between the inductive and capacitive reactance.

Now suppose we have a circuit containing 3 ohms of resistance in series with a 4 ohm inductive reactance and we want to wipe out the inductive reactance. All we have to do is to place 4 ohms of capacitive reactance in series with the resistor and the inductance as in Fig. 15. The current is 10 ÷ 3 or $3\frac{1}{3}$ amperes, for X_L balances out X_C and *R* (3 ohms) is the only impedance in the circuit. The voltages across parts are as follows: $V_L = 4 \times 3\frac{1}{3} = 13.3$ volts; V_R is equal to 10 volts; V_C equals 13.3 volts.

Again suppose we have a series circuit as shown in Fig. 16 with X_L equal to 4 ohms, X_C equal to 4 ohms and *R* equal to .1 ohm. What are the current and voltage across the parts? You know X_L is cancelled by X_C so that the circuit is really equivalent to a circuit containing only .1 ohm of resistance. The current then will be $\frac{10}{.1} = 100$ amperes. $V_L = 100 \times 4 = 400$ volts; $V_C = 100 \times 4 = 400$ volts and $V_R = 100 \times .1 = 10$ volts. It

seems queer that we apply only 10 volts and still the voltage across the coil and across the condenser is 400 volts, 40 times the terminal voltage. And yet as you see it is perfectly possible.

Whenever in a series circuit the capacitive reactance balances out the inductive reactance, the circuit is *in resonance* with the frequency of the source of e.m.f.

But a circuit having fixed values of inductance and capacity can be in resonance with only one particular frequency. When the frequency changes the circuit is thrown out of resonance immediately. We can see why this should be if we take a rapid glance at the formulas for inductive reactance and capacitive reactance which we learned about before. You know that $X_L = 6.28$ times the frequency in cycles, times the inductance in henries ($X_L = 2\pi fL$), which tells us that as we increase the frequency through a coil the reactance of the coil increases. On the other hand, X_C is equal to 1 divided by 6.28 times the frequency, times the capacity in farads ($X_C = \frac{1}{2\pi fC}$). From which we can see that as the frequency is increased the capacitive reactance decreases.

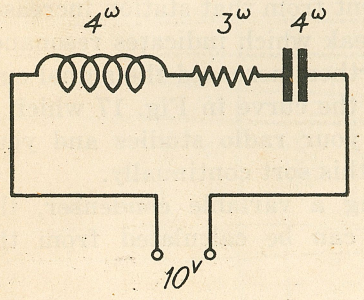


Fig. 15

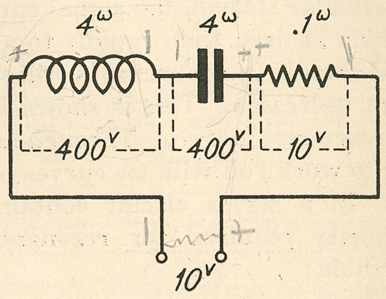


Fig. 16

Keeping this in mind let us examine a typical resonant circuit, containing a variable condenser and a coil. Of course there will be resistance in the coil, and there will be distributed capacity besides the inductive reactance. In order to obtain maximum current flow at a certain frequency, the condenser must be set at a point where the capacitive reactance will exactly balance the inductive reactance. This is exactly what you do when you tune a radio set. Of course we might have had a fixed condenser and a variable coil, but it is customary in receivers to use variable condensers to tune resonant circuits.

The station to which you tune broadcasts on a certain frequency. The signal induces a voltage into the series A.C. circuit and the reactance of the coil and condenser will depend on that frequency. If the capacitive reactance is very different from the inductive reactance, the total impedance in the circuit will be high and the signal will be killed.

But we tune the circuit by changing the capacity and as the capacitive reactance approaches the value of the inductive reactance the current in the circuit becomes larger and larger until it reaches a maximum value. At this point the circuit is in resonance with the broadcasting station. If you change the adjustment of the condenser beyond resonance the current will go down, for as you detune the circuit, the impedance increases to a point where no signal current can flow.

When the capacity is increased toward resonance with a particular station, the signal current from that station increases slowly at first, then rapidly to a peak which indicates resonance and then if the capacity is still further increased the signal current decreases. This is shown by the curve in Fig. 17 which is a *resonance curve*. Throughout your radio studies and your radio work you will use curves of this sort continually.

In a series circuit containing a variable condenser, the capacity required for resonance can be calculated from the formula:

$$C = \frac{1}{39.3 f^2 L}$$

where $C =$ capacity in farads
$f =$ cycles per second (frequency)
$L =$ inductance in henries

There is also a formula to be used with circuits where the condenser is fixed and the inductance variable (a variometer). Resonance occurs when:

$$L = \frac{1}{39.3 f^2 C}$$

Let's consider another case, as shown in Fig. 18a where both the capacity and the inductance are kept fixed but the frequency of the signal—either from a generator or from a broadcasting station, is increased. The result is shown in Fig. 18b. At first the circuit acts as though only a condenser were in it.

Then the impedance becomes less and less as the frequency is increased until the condition of resonance appears when the impedance is zero. As the frequency is increased beyond this point the circuit acts as though it had only a coil in it and the impedance gradually increases.

There is a formula for the resonant frequency, which is one of the most important formulas in Radio. It is:

$$\boxed{f = \frac{1}{6.28\sqrt{LC}}}$$

From this formula we can calculate the natural frequency of any series A.C. circuit if we know the values of the inductance and capacity.

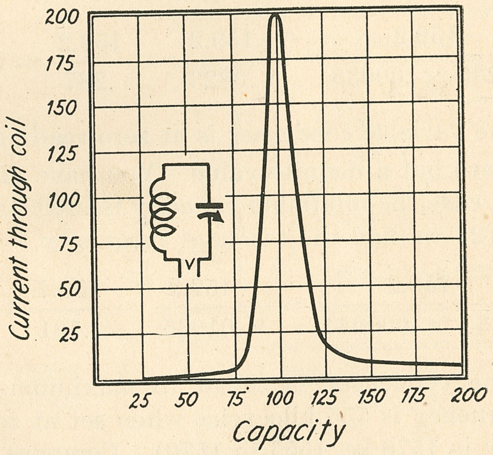


Fig. 17

For example: Manufacturers employ radio frequency coils having an inductance of 235 microhenries (.000235 henries), shunted by a variable condenser whose maximum capacity is .00035 microfarads. The minimum capacity will be about ⅛ of this maximum or about .000044 microfarads. To what maximum, to what minimum frequency will such an arrangement resonate?

(1) The formula is $f_{\text{resonant}} = \frac{1}{6.28\sqrt{LC}}$

where f is in cycles per second
L is in henries
C is in farads

Now we all know that when dealing with broadcast receivers the frequency is usually expressed in kilocycles per second (1000 cycles make one kilocycle), inductance is expressed in microhenries (1,000,000 microhenries to make one henry) and the capacity is expressed in microfarads (1,000,000 microfarads make one farad). For this reason the formula is more conveniently expressed:

$$(2)\ f_{\text{kilocycles}} = \frac{159.2}{\sqrt{L_{\text{microhenries}} \times C_{\text{microfarads}}}}$$

Of course you can use the first formula but remember to express inductance in henries and capacity in farads, and don't forget that the answer will be in cycles per second.

At maximum capacity $L = 235\ \mu\text{h}$ and $C = .00035\ \mu\text{f}$. By substituting in (2) the resonant frequency is:

$$f\text{, kc.} = \frac{159.2}{\sqrt{235 \times .00035}} = \frac{159.2}{\sqrt{.0823}} = \frac{159.2}{.287} = 555 \text{ kilocycles.}$$

When the variable condenser is at zero reading the capacity will not be zero but a definite value. You have already studied this. In this case the minimum capacity is $.000044\ \mu\text{f}$. By substituting in (2) we find the resonant frequency,

$$f\text{, kc.} = \frac{159.2}{\sqrt{235 \times .000044}} = \frac{159.2}{\sqrt{.01035}} = \frac{159.2}{.101} = \begin{matrix}1570\\ \text{kilocycles.}\end{matrix}$$

When the condenser is tuned to maximum capacity the resonant frequency is 555 kilocycles when set at zero the resonant frequency is 1570 kc. (555 to 1570). Compare this with the actual band of 550 to 1500. Just not low enough at the low end. The manufacturer would merely add on a turn or two and the correct range would be obtained. Now the condenser would tune in all stations in the broadcast band when rotated.

REACTANCES IN PARALLEL CIRCUITS

Coils and condensers are not always connected in series—in receivers and transmitters you will often find them in parallel. Of course in any circuit there is resistance but in resonant circuits it is undesirable and we keep it down to a minimum.

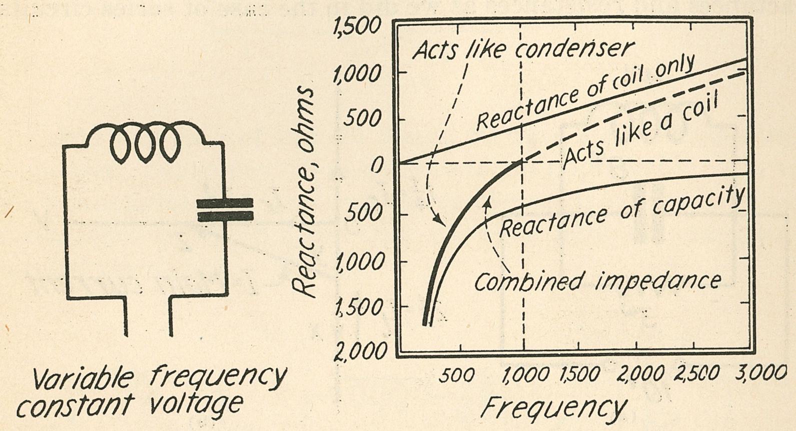
For the sake of completeness we have included a resistor in Fig. 19a which represents the resistance of the other devices and the conductors in the circuit. Let us say it is 3 ohms, that the capacitive reactance in this circuit is 8 ohms, and the inductive

reactance 4 ohms. The supply voltage is again 10 volts. Now we are interested in the current drawn by each and the current drawn by the three together.

It won't be at all difficult to determine the current drawn by each part if the device has 10 volts across it. From Ohm's law we know that I_L will be 10/4 or 2½ amperes; I_C will be 10/8 or 1¼ amp.; and I_R will be 10/3 or 3⅓ amp.

This of course follows from the rule we learned to the effect that no matter where a reactance or an impedance is in a circuit, the current through it is the voltage divided by the impedance, reactance or resistance as the case may be.

Is the main current 2½ + 1¼ + 3⅓ amp.? It would be if we did not have to consider phase. In calculating the total current we must remember that inductive reactance throws its current and voltage 90 degrees out of phase and capacitive reactance also throws its current and voltage 90 degrees out of phase but in the opposite direction.



(a) (b)

Fig. 18

Each separate current has a definite phase relation to the voltage across that particular device. But we know that the voltage across each is the same. Therefore, we can refer each current to a common voltage. Again we use a line diagram. Let line *OV* in Fig. 19b be our common voltage. Then current I_l lags behind its voltage V by 90 degrees. On the line I_l we mark off 2½ units representing 2½ amperes of current. I_C, the current through the capacity, leads its voltage by 90 degrees. On its line we mark off 1¼ units representing 1¼ amp. Because the current through a resistor is always in phase with its voltage we mark off on line OV $3\frac{1}{3}$ units representing the $3\frac{1}{3}$ amp., through the resistor. Considering the current in the line diagram we must subtract I_C from I_l. We do this by marking off I_C on I_l starting at point x. From point y to point z we draw a line and the length of this line represents the total current in the circuit. Measuring it we find it is $3\frac{1}{2}$ units long from which we know that the total current is $3\frac{1}{2}$ amperes.

Now that we know the total current, it is a simple matter to calculate the total impedance—we merely divide 10 by 3.5 which is 2.85 ohms. In working with parallel circuits it is always much easier to find the total current by means of a line drawing and then to calculate the total impedance, than to calculate the impedance first. If you were to make a line drawing of the reactances and resistances as we did in the case of series circuits, we would find that the total impedance would be 5 ohms. This is obviously wrong for we have found that the impedance is only 2.85 ohms. If we think a minute, however, we will realize that this difference is to be expected for in parallel circuits several paths are provided for the current to flow over, and the more paths, of course the less impedance.

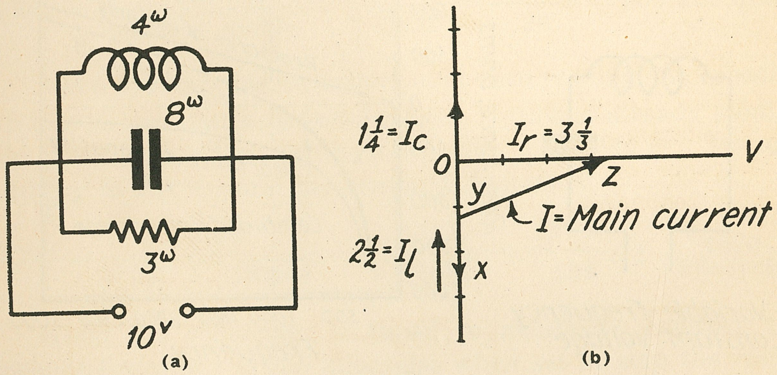


Fig. 19

From the line diagram in Fig. 19b we can see that the current through the coil was balanced out by part of the current in the condenser. We could go a step farther—we could vary the capacity until its reactance would be equal to 4 ohms. Then the current in the condenser would completely balance out the current in the coil and we would have parallel resonance. In parallel resonant circuits, the only current that flows in the main circuit is due to the resistance.

The resonance formulas given in the chapter on series circuits, apply here as well. It should be remembered, however, that in series circuits, resonance occurs when the voltages across the resistance balance out—but in parallel circuits resonance appears when the *currents* through the reactances balance each other and wipe each other out.

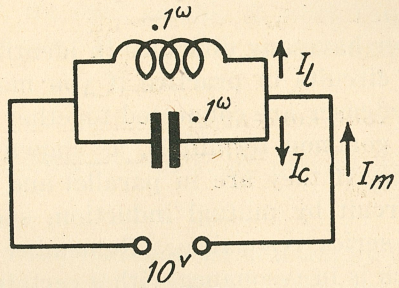


Fig. 20

And now look at Fig. 20 where we have a coil shunted by a condenser. Let us say the resistance is not appreciable. The coil has a reactance of .1 ohm and the condenser is adjusted to have a reactance of .1 ohm, so that we have here an example of parallel resonance.

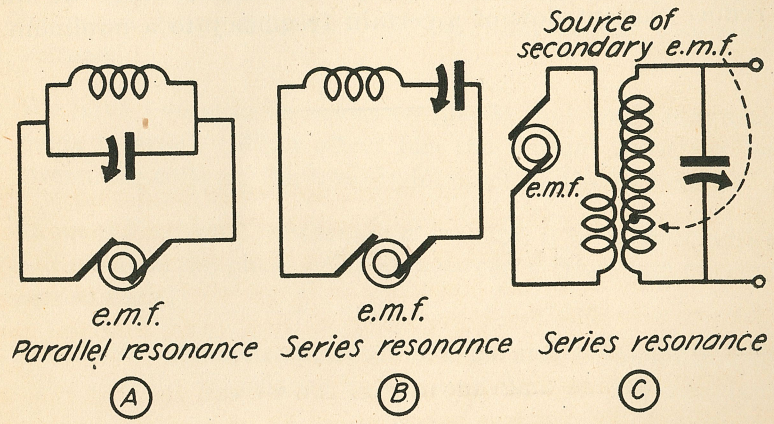


Fig. 21

The current through the coil I_l is $10 \div .1$ or 100 amperes. The current through the condenser I_C is $10 \div .1$ which is also 100 amperes. When these two currents are added by means of a line diagram you will find that one balances out the other and the line current I_M is zero. This seems peculiar but it is true.

And as no current flows in the line, it is clear that the coil and condenser in a parallel resonant circuit act like one extremely large impedance. Remember this last statement as it is very valuable in Radio.

In your radio work you will often find parallel circuits like this connected in various parts of receivers to prevent current from flowing. A parallel resonant circuit may be used as a choke or as a wave trap.

You will never have any difficulty in identifying series and parallel resonant circuits in practice if you memorize Fig. 21. If the coil and condenser are connected together and the voltage is applied to the common terminals, as shown in A, we have parallel resonance. If they are in parallel and a voltage is induced into the circuit by mutual induction, such as shown in Fig21C, we have series resonance. Remember also that in a series circuit which is in resonance with a certain frequency, the impedance is limited to the resistance in the circuit. In parallel resonant circuits, in resonance with a certain frequency, the impedance is extremely high and the current flow is limited to the current flow through the equivalent parallel resistance, which is usually extremely high. We use a series resonant circuit where we want to obtain maximum current flow at a certain frequency. We use a parallel resonant circuit where we want to reduce current flow of a certain frequency to a minimum.

TEST QUESTIONS

Number your answers 9FR and add your *student number*.

Never hold up one set of lesson answers until you have another set ready to send in. Send each lesson in by itself before you start on the next lesson.

In that way, we shall be able to work together much more closely, you'll get more out of your course, and the best possible lesson service.

1. What is the difference between mutual induction and self-induction?
2. How can a voltage be induced in a coil by the magnetic field of another coil, without moving either coil?
3. What kind of current flows in the secondary of a transformer?
4. Explain the difference between a step-up and a step-down transformer.
5. If 110 volts are fed to the primary of a step-up transformer having a turn ratio of 1 to 10, what is the secondary voltage?
6. We have two coils in series so placed that their magnetic fields interact. What effect has the mutual induction between the coils on the total inductance of the two coils?
7. In an A.C. circuit containing a resistor, a condenser and a coil, what is the phase relation between voltage and current across each?
8. Does a series resonant circuit or a parallel resonant circuit offer infinite impedance to current flow at the resonant frequency?
9. In what ways can a resonant circuit be tuned to various frequencies?
10. If in an A.C. circuit we measure the current through a certain device and find it is 2 amperes and the voltage across it is 110^v, what is the impedance of the device?

$$\begin{array}{r}110\\10\\\hline 1100\end{array}$$

1. a Regenerative type of Receiver.

2 Spark coil type, Electrolytic Interrupter, and constant current arc

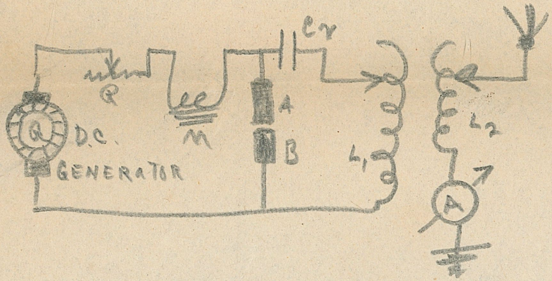
3. They are used on board Ship. They are used as auxillary equipment in case of breakdown of other apparatus.

4. It consist essentially of an arc generator as oscillator with a crystal Detector.

5. By using a circuit interrupter in series with a crystal Detector and headphones.

6. No. It is not the right Frequency.

7.

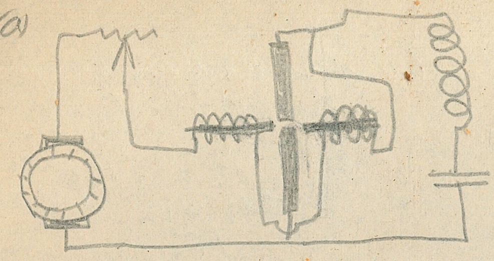


8 (1) Can operate at much higher Frequency has a larger range.
(2) Can have almost indefinit amount of amplification.

9 as the Rotor revolves the flux threading the ar Armature Coil rises and falls due to the alternate Break and make of the magnetic circuit. this induces in them an alternating voltage.

10. The difference lies in the fact that the Goldschmidt acts on the principle of Reflection while the alexanderson does not.

1. (a)



(b) the line voltage charges the condenser, after it is charged the collapsing of the field of the coil adds to its potential making it about twice the line voltage, this then feeds back into the line the coil then gain Magnetic energy and condensers voltage is below the line this completes one cycle. other cycles follow in succession.

2 When the Key is pressed maximum antenna current flows, When it is open the current flows in the dummy antenna. as the Keying is continued only the current as the Key is depressed is allowed to flow in the antenna. This forms the dots and dashes.

3. (a) To keep the arc gap clear of the ionized gas formed. (b) at right angles to the electrodes.

4. (a) Carbon & Copper, (b) to keep the disintegration of the electrodes even. (c) to Keep the electrodes from melting.

5. (a) $\frac{1}{32}$ inch, (b) as far as possible without stopping the arc,

6. The Series resistor switch may be closed shorting the Generator, burning it out.

7. By placing a Resistor in the antenna circuit.

8. From the arc the current flows to the antenna circuit, where, when the Key, which is in series with a relay, is pressed operates this relay draws a contact point to it, This contact is the connection from the arc to the antenna, by this means the current may be made to flow in the antenna circuit or in the dummy antenna circuit.

9. (1) By Bringing an iron disc close to the Back shunt inductance coil. (2) a secondary with a resistance as its load is coupled to the shunt coil, by varying the resistance the inductance or frequency may be varied.

10. Circuit of 2 Kw arc ~~Transils~~